analysis shows the selling price of electricity to be 6.75 ¢/kWh in current dollars or 5.25 ¢/kWh in constant dollars for the system design described above.

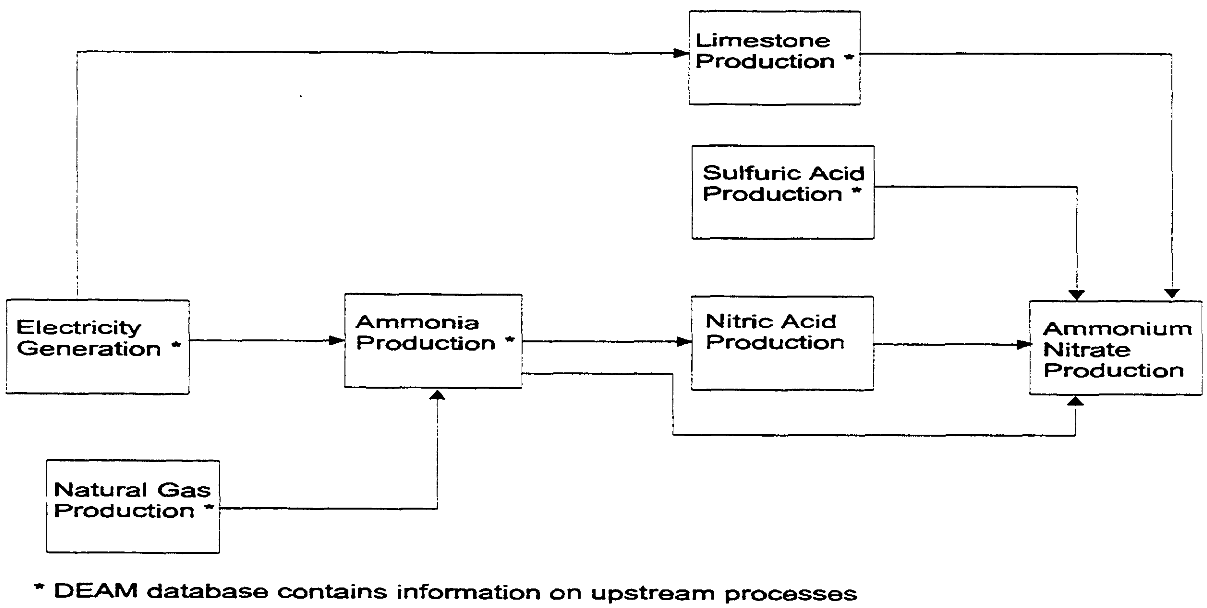
Table 9: Summary of Technoeconomic Analysis Results

Output (MWe)	113
Efficiency (HHV)	37.2%
Capital cost (TCR, $/kW)	1,187
Operating cost including fuel ($1,000/yr)	25,891
COE (¢/kWh, Current $)	6.75
COE (¢/kWh, Constant 1990$)	5.25

4.0 Description of Process Blocks Studied in the LCA

The subsystems included in this life cycle assessment are biomass growth, transportation, and electricity production. Refer again to Figures 3 and 4 for the processes within these subsystems. Material and energy flows were quantified for each process block; details about the assumptions and data sources are given in the subsequent sections. To visualize how each upstream process is integrated with others in the system, the screen printouts from the TEAM software are attached as Appendix A. Emissions and energy use of some of the upstream processes were taken from the DEAM database (see section 2.5). The following schematic of the process blocks required for ammonium nitrate production serves as an example of how the total material and energy requirements for an intermediate feedstock were assessed. The data in some of the DEAM databases include the corresponding upstream processes in the block itself (e.g., natural gas production and reforming are included in ammonia production); these blocks are denoted with an asterisk.

Schematic Showing Process Blocks for Ammonium Nitrate Production



The emissions, resources, and energy associated with electricity production for use in upstream process blocks were taken from the DEAM database. The generation mix was that of the mid-continental United States, which according to the National Electric Reliability Council, is composed of 64.7% coal, 5.1% lignite, 18.4% nuclear, 10.3% hydro, 1.4% natural gas, and 0.1% oil; distribution losses are taken at 7.03%. It was assumed that the electricity produced by this biomass power plant will not significantly alter the generation mix given the current size of the market. Natural gas, diesel, and coal production, also taken from the DEAM database, include extraction, processing, and transportation.

4.1 Base Case Feedstock Production Assumptions

4.1.1 Yield Assumptions and Land Requirements

Biomass for the power plant is assumed to be hybrid poplar, grown as an energy crop specifically for this use. The plantation was assumed to surround the power plant, located in the North-Central Iowa/South-Central Minnesota region of the United States. Defining the site more specifically was originally included in the scope of this project, but deemed unnecessary since site-specific data are generally not available. Rather, average values from test plots were used. A significant amount of data was obtained directly from researchers at Oak Ridge National Laboratory (ORNL). Although published information exists, some from ORNL itself, a notable amount of experience has been gained in recent field trials. ORNL is currently preparing much of the information used for publication.

For the base case analysis, the yield of biomass was assumed to be 13.4 dry Mg/ha/year (6 dry t/acre/year) (ORNL, 1996), grown on seven year rotations. Graham *et al* (1992) report current and expected yields for different regions in the country. For comparison with that being used in the LCA, this information is shown in Table 10. Yield increases were assumed to occur through scientific improvements (such as better breeding) or specific favorable climate conditions, rather than increased fertilizer use. Thus, the amount of fertilizer applied per acre was not varied in relation to yield. The current analysis assumes equal rates of biomass growth for each year that a stand of trees is in production. However, growth rate is almost certainly higher earlier in the rotation (Marland and Marland, 1992), resulting in a declining rate of carbon absorption as the trees mature. When a continuous supply of biomass is needed, the rates average out to those used in this study. However, in the early years of system operation, years negative seven through about negative four, higher growth rates will mean greater removal of CO_2 from the atmosphere. Similarly, as the biomass plantation begins to slow its supply to the plant, the net CO_2 released will increase. It's important to note that over a seven-year time-frame, though, the average net CO_2 emissions will be the same.

Table 10: Short Rotation Woody Crop Yields

Region of U.S.	Current yields	Goal	Maximum observed yields
	(bone dry Mg/ha/yr)		
Northeast	9.0	15.7	15.7
South/Southeast	9.0	17.9	15.7
Midwest/Lake States	11.2	20.2	15.7
Northwest	15.7	29.1	43.3
Subtropics	15.7	29.1	27.6

The ASPEN Plus™ simulation gives an average biomass feed requirement of 1,334 bone dry Mg/day (1,470 bone dry tons/day). If an 80% capacity factor is assumed, the average feedstock requirement at the plant gate is reduced to 1,067 dry Mg/day. Later sections will discuss a sensitivity analysis that was performed on operating capacity. Pre- and post-haul losses were based on field trials, and were assumed to be 13.35% and 4.62% of the standing yield, respectively (Perlack *et al*, 1992). Because the biomass is grown on seven year rotations, seven fields will be producing the full feedstock requirements of the plant.

At the base case yield, and including pre- and post-haul losses, the amount of land that will be dedicated to producing biomass for the plant is 44,135.6 ha. Assuming that only 10% of the land surrounding the power plant can be used for dedicated feedstock production, the total area around the plant that contains these plantations increases to 441,356 ha. Without choosing a specific site and mapping out the land availability and transportation routes, the average distance to the power plant was determined from an algorithm developed by R. Overend (1981) and now in wide-use in the forest industry. In the calculations, a tortuosity factor of 1.3, with 1.0 representing line-of-site, was assumed. This results in an average biomass haul distance of 27.6 km.

4.1.2 Base Case Fertilization Assumptions

Hybrid poplar requires less fertilization than most traditional row crops such as corn, but field trials indicate that nitrogen, phosphorus, and potassium fertilizers will be necessary. However, short rotation woody crops might be able to absorb the needed nutrients from run-off if they are planted at the periphery of traditional agriculture fields, solving two environmental problems at once. In the base case, nitrogen fertilizer was assumed to be applied at a rate of 100 kg/ha nitrate in year four (Tuskan, 1996). Field trials have demonstrated that growth is enhanced by nitrogen fertilization only after the second year, and that by waiting to apply fertilizer until it can be readily absorbed by the root system, movement of nitrate compounds from the plantation and into the surrounding environment can be mitigated. The nitrate was assumed to be supplied as a 50/50 mixture of urea and ammonium nitrate, the two most common forms. The form applied on an actual field will depend on many factors, including regional requirements and what the farmer traditionally uses on other crops. Phosphorus was assumed to be applied as triple superphosphate, at a rate of 22.4 kg/ha as P (Tuskan, 1996) in year one of the seven year rotation. Also in the first year, potassium, or potash fertilizer, was applied as K_2O at a rate of 39.2 kg/ha as K. Potassium or potash fertilizers were not required in subsequent years.

Greater than 95% of commercial nitrogen fertilizers are derived from synthetic ammonia, of which 85% is dedicated to this use. Ammonium nitrate is produced via a reaction between nitric acid, produced by catalytic oxidation of nitrogen with ammonia, and ammonia produced by catalytic steam reforming of natural gas and subsequent catalytic ammonia synthesis. Limestone and sulfuric acid are used in the prilling process once the ammonium nitrate has been manufactured. The required amounts of ammonia, 60% nitric acid solution, limestone, and sulfuric acid are 0.21, 0.77, 0.03, and 0.01 kg, respectively, per kg of ammonium nitrate (SRI, 1995). Emissions include ammonia released to the air, ammonia and nitric acid released to water systems, and particulates from prilling operations, in amounts of 0.075, 0.018, 0.001, and 0.001 kg per kg of product (U.S. EPA, 1995). The process blocks that were included in the LCA for the production of ammonium nitrate were nitric acid production, sulfuric acid production, limestone production, ammonia production, natural gas production, and electricity generation.

Urea is made in a high-temperature and high-pressure reaction between 0.57 kg of ammonia and 0.75 kg of carbon dioxide (SRI, 1995). Additionally, 0.022 kWh electrical energy input is required per kg of product. In the manufacturing process, ammonia and particulates are emitted to the atmosphere at the rate of 0.0122 and 0.0007 kg per kg of urea (U.S. EPA, 1995).

Nitrous oxide (N_2O) may be produced during nitrification processes at the plantation. Bouwman (1989) estimates that the emissions induced by nitrogen fertilization on cultivated fields is equal to 0.5-2% of the nitrogen applied. In this assessment, the higher number was assumed for the base case.

The data for granular triple superphosphate production and potash fertilizer production were taken from the DEAM database. The principal emission is CO_2 at rates of 0.02 kg/kg granular triple superphosphate and 0.002 kg/kg K_2O. Additionally, small amounts of hydrocarbons, NOx, and SOx are produced because of fossil fuel combustion for energy generation.

4.1.3 Base Case Herbicide and Pesticide Use

From experience gained in hybrid poplar field trials, herbicide application has been found to be necessary for the proper growth and survival of young trees (Tuskan, 1996). For the LCA, both a pre-emergent herbicide (Oust™ by DuPont) and a post-emergent herbicide (Roundup™ by Monsanto), were assumed to be used. The application rate of each is 36.5 cm^3 of active ingredient per hectare in the first and second years of each crop rotation (Tuskan, 1996). These herbicides will be applied before planting and during crop establishment; no herbicide applications are expected to be required once canopy closure occurs. In addition to the application of chemical herbicides, mowing down emerging weeds and physically removing them from the field may also be practiced. However, this was not assumed in the LCA.

Because the processes to manufacture Roundup™ and Oust™ are proprietary, very little information on material and energy balances is available. Therefore, the emissions associated with their production were not included in the life cycle inventory; however, the quantity used is so low as to be negligible. Turhollow and Perlack (1991), however, report that 418 MJ of energy are required to produce each kg of active ingredient. Liquid fuel (60%), natural gas (23%), and electricity (17%), are the primary sources. This energy requirement, plus the energy and emissions resulting from extraction, processing, and use of the fossil fuels, were included in the assessment.

Like many other farm chemicals, herbicides are strongly adsorbed onto soil particles. Thus, undesirable movement of herbicides will occur mainly by erosion from the field. However, the ultimate effect on the environment from such movement will depend on the life of the chemicals released and the effect of the resulting species. Riparian filter strips, if used, are likely to remove much of the herbicide in the run-off, especially those substances that degrade quickly (see Sears, 1996, for a more detailed discussion on riparian filter strips). Material safety data sheets (MSDS) for each herbicide were used as a basis for discussing the environmental implications of their use.

Isopropylamine salt of glyphosate, also known as Roundup™, is manufactured by Monsanto and primarily used as a post-emergent herbicide. It's activity is limited to blocking a plant's ability to manufacture certain amino acids. Direct contact by humans may cause temporary eye irritation and conjunctivitis, while prolonged exposure may cause dermal irritation. Ingestion has produced nausea and vomiting. The MSDS reports the oral LD50 to be 5,400 mg/kg, which Monsanto states to be practically nontoxic. The inhaled LC50 after four hours is 3.18 mg/liter, and reported as slightly toxic. Human testing produced no irritating or sensitizing effects. Roundup™ was found to be slightly to moderately toxic to marine wildlife. Before Roundup™ is degraded by microbial activity to CO_2 and water, it strongly adheres to soil particles, making movement from the plantation unlikely.

Sulfometruron methyl, manufactured by DuPont under the label Oust™, is used as a pre- and post-emergent weed killer. Oust™ is soluble to only 10 ppm in water at pH 5.5, and 70 ppm in water at pH 7. In contrast, it is soluble to 2,380 ppm in acetone. Therefore, significant water pollution by Oust™ is not expected. The hydrolysis rate (i.e., decomposition rate) of Oust™ in water is shown in Table 11. The half-life of Oust™ in soil was found to be approximately four weeks in warmer weather conditions in Delaware and North Carolina. Degradation in cold conditions is near zero, and is lower in highly alkaline soils than acidic soils. Additionally, adsorption is higher in acidic soils, while mobility is more likely in alkaline soils.

Table 11: Hydrolysis Rate of Oust™ Herbicide

	Half-life (hours)			
Temperature	pH 2	pH 5	pH 7	pH 9
25°C	100	475	>1000	>1000
45°C	6	33	150	180

Source: Oust MSDS, DuPont

The LD50 is reported in the MSDS to be greater than 5,000 mg/kg for male and female rats. Based on skin absorption, the LD50 is greater than 8,000 mg/kg for male rabbits, and greater than 2,000 for female rabbits. The inhaled LC50 is greater than 5 mg/liter for a four hour exposure. At concentrations of 75% and less, Oust™ was not found to be a skin irritant or a permanent eye irritant. Hematological (blood) and biliary and hepatic (liver) effects were observed; histopathological and reproductive effects were not observed. Oust™ was not found to cause teratogenic or mutagenic effects.

The use of pesticides to control insects and small mammals on hybrid poplar plantations is expected to be unpredictable and sporadic (Tuskan, 1996). The amounts will likely be small if any. Furthermore, alternative methods such as natural barriers and breeding pest resistance into the trees may be able to eliminate pesticide use altogether. For these reasons, use was assumed to be zero, although because the environmental implications of pesticide use are generally serious, further study into this matter is warranted.

4.1.4 Water Consumption by Biomass Plantation

All water required by the biomass as it grows was assumed to be supplied by rainfall. Therefore, the resources consumed do not include water depletion at the plantation. Also, emissions and energy use do not reflect any irrigation practices should they be used.

4.1.5 Biogenic Emissions

Emissions of biogenic compounds from deciduous trees (hardwoods), including poplars, are mainly isoprene. Coniferous forests, on the other hand, emit mainly monoterpene (including alpha and beta pinene). Little data on biogenic emissions exist for hybrid poplar, and because the region in which the trees are grown can influence the amount and effect of these emissions, the data that do exist may have significant error. Additionally, it should be noted that isoprene emissions vary by season, with little-to-none after leaf-fall, and higher amounts during hot weather periods.

Perlack *et al* (1992), predicted emissions at five different hypothetical test sites to range between 189 and 1,600 kg/ha/year. However, emissions for four of the five sites are between 305 and 616 kg/ha/year, with an average of 476 kg/ha/year. This average, because it fit well within the bounds of the site with the greatest variance, was chosen as the base case value. P. Hanson at ORNL is now completing a study that translates other literature values, some of which are based on field trials, into yearly averages. Although this study is not yet published, preliminary data indicate that the range reported by Perlack *et al* is consistent with other measurements on the low end, but that the high end significantly overstates likely isoprene emissions.

4.1.6 Transportation of Farm Chemicals

Fertilizers and herbicides required to grow biomass were transported from their point of production to the plantation. Because the actual location of the plantation was not set for this analysis, the transportation was assumed to be 60% by rail and 40% by truck over an average distance of 640 km (Pimentel, 1980). Light fuel oil and diesel are used in the trains and trucks, respectively. As with the analysis of transporting the biomass (discussed in section 4.2), the energy and resource consumption of manufacturing trains and trucks were included in the LCA. The emissions produced and energy used to manufacture the fuels were taken from the DEAM database, of which Appendix B contains information for several of the database modules. Included are the assumptions used in each deriving each database module and the source(s) where the various data was obtained.

4.1.7 Plantation Operations

Energy is consumed and emissions are released for each operation required to plant, grow, and harvest biomass. Table 12 shows the activity and machinery used in each year of the seven year rotation. The materials that were required to manufacture each piece of equipment were calculated based on weight (Morbark, 1993) and ORNL's BioCost software documentation (Walsh, 1996). For simplification, only steel and iron are assumed to be used in farm equipment construction, at 98% and 2%, respectively, of the total weight.

Table 12: Plantation Operations and Necessary Machinery

Year of rotation	Operation	Machinery	Tractor needed, hp (kW)
1	Plow Disk Plant Apply herbicide Apply P and K fertilizers Cultivate	6-16" Moldboard plow 33' Tandem disk 35' Grain drill 50' Boom sprayer 40' Fertilizer spreader 2-36" Row cultivator	180 (134) 180 (134) 180 (134) 60 (45) 60 (45) 60 (45)
2	Apply herbicide Cultivate	50' Boom sprayer 2-36" Row cultivator	60 (45) 60 (45)
3	No activity		
4	Apply nitrogen fertilizers	40' Fertilizer spreader	60 (45)
5	No activity		
6	No activity		
7	Harvest and bunch Skid Chip	Feller buncher head Skidder Chipper	100 (75) none none

The number of hours required for the piece of equipment to cover an acre of land was calculated by the following formula (Walsh, 1996):

$$\text{Hours/acre} = 8.25 / (MS * MW * FE) \qquad \text{Equation 1}$$

where MS = the typical operating speed of the machine (miles/hour)
MW = the operation width of the machine (feet)
FE = the average field efficiency of the machine (percent)
8.25 = conversion factor derived by ORNL

The amount of steel used in manufacturing each machine, per acre of biomass in production, was calculated from the following formula (Walsh, 1996). The emissions and energy used to manufacture this steel, as well as to recycle it at the end of the service life, are part of the DEAM database. For each piece of equipment, such data are incorporated into the analysis in the years that manufacturing and decommissioning occur to reflect the true stressors on the environment.

$$\text{Steel/acre} = W * 0.98 / APH / NH \qquad \text{Equation 2}$$

where W = the weight of the machine (lb)
APH = acres per hour, the inverse of that calculated in the previous formula
0.98 = the fraction of the total weight that is steel
NH = average annual use (hours)

The calculation for the amount of iron used per acre is the same as for steel except that 0.02 is the fraction of the total weight that is iron. Table 13 gives the parameters and results of these calculations for machinery complements (those that require a tractor for operation). Similar data for harvesting equipment and tractors are shown in Table 14.

Table 13: Materials Required for Machinery Complement Construction

Complement	Operating speed (miles/hr)	Operation width (feet)	Average field efficiency	Acres per hour	Weight (lb)	Average annual use (hr)	Pounds of steel per acre	Assumed lifetime (hr)	Pounds of iron per acre
6-16" Moldboard plow	4.5	10.7	85	4.9	5,000	200	5.0	2,000	0.10
33' Tandem disk	6	33	80	9.6	11,190	200	5.7	2,000	0.11
35' Grain drill	5	35	70	14.8	8,000	120	4.4	1,200	0.09
50' Boom sprayer	7	40	70	23.8	3,000	120	1.0	1,500	.0.02
40' Fertilizer spreader	3	50	60	10.9	1,000	150	0.6	1,200	0.01
2-36" Row cultivator	6	6	80	3.5	250	60	1.2	600	0.02

Table 14: Materials Required for Harvesting Equipment and Tractor Construction

Equipment	Acres/hour	Weight (lb)	Average annual use (hr)	Pounds of steel per acre	Assumed lifetime (hr)	Pounds of iron per acre
Feller buncher head	0.83	3,600	500	8.5	2,000	0.17
Skidder	0.11	5,000	2,000	23.0	10,000	0.45
Chipper	0.26	30,000	2,000	56.2	10,000	1.11
60 hp tractor	1.43	4,800	330	10.1	12,000	0.20
100 hp tractor	0.83	11,000	500	26.1	12,000	0.52
180 hp tractor	2.0	16,000	520	14.4	12,000	0.28

Fossil fuel use in farming operations was calculated by ORNL's BioCost software (Walsh, 1996). Equations 3 and 4 are those that this package uses to calculate the fuel and lubricating oil requirements, in gallons per acre, for farming operations. The oil was assumed to be combusted in the engine since data on the fate of lubricating oil are not available. The fuel and lubricating oil for all farm operations was assumed to be diesel and light fuel oil, respectively.

$$\text{Fuel} = (\text{HP}/2) * 0.0988 / \text{APH} \qquad \text{Equation 3}$$

$$\text{Oil} = 0.00573 + 0.0021 * \text{HP} \qquad \text{Equation 4}$$

where HP = the horsepower of the piece of equipment
0.0988 = conversion factor derived by ORNL
APH = acres per hour calculated in previous equations

The annual fuel and oil requirements are shown in Table 15.

4.1.8 Soil Carbon Sequestration Base Case

Soil carbon is defined to be non-living organic matter integrated with mineral matter. The soil on which hybrid poplar is grown has the potential to sequester carbon such that the total amount of atmospheric carbon that is absorbed by the biomass is more than that contained in the biomass to the power plant. Unfortunately, the ability of soil to sequester carbon is very site-specific and difficult to measure. Furthermore, very few studies specific to energy crops have been conducted. Thus, the data in the literature are sparse and contradictory, making any statistical analysis infeasible. Hansen (1993) says that there will be a loss in soil carbon with trees in cycles of less than six years, and a gain in older stands, particularly ones that are greater than twelve years old. Most importantly, Hansen also reports that within eight to ten years after the plantation is retired, soil carbon reverts back to pre-plantation levels. Perlack *et al* (1992), estimated the amount of soil carbon increase to be between 13.4-17.9 Mg/ha over a seven year rotation. Schlamadinger and Marland (1996) reported information from Ranney, Wright, and Mitchell at ORNL that soil carbon will increase by 40.3 Mg/ha over a seven year rotation, although this number is generally seen to be a very special case. In 1994, Ranney and Mann reported that soil carbon would increase by approximately 30-40 Mg/ha over 20-50 years, then come to equilibrium, resulting in only a short-term increase in the net amount of CO_2 removed from the atmosphere. More recent research by Grigal and Berguson (forthcoming) found no difference in soil carbon in six to 15 year-old hybrid poplar plantations in Minnesota compared to adjacent row crops or hayland. Additionally, carbon sequestration will vary according to the seasons and tilling practices (Reicosky *et al*, 1995). Because the actual amount sequestered will be highly site specific, and given that the values in the literature vary so widely and are based on a small number of field trials, it is impossible to say what constitutes a representative value. Therefore, a range of values was incorporated into the sensitivity analysis, with the base case assumption that there will be no net soil carbon gain or loss.

Table 15: Annual Fuel and Oil Requirements for Farming Operations							
Year	Number of fields in production	Number of acres in production	Number of hectares in production	Diesel fuel (gal/acre)	Diesel fuel consumed (gal)	Oil (gal/acre)	Oil Consumed (gal)
-7	0.5	5,897	2,388	0.64	3,757	0.00	10
-6	1.5	17,692	7,163	0.97	17,212	0.00	44
-5	2.5	29,487	11,938	0.97	28,687	0.00	73
-4	3.5	41,282	16,713	0.99	40,869	0.00	104
-3	4.5	53,077	21,488	0.99	52,546	0.00	134
-2	5.5	64,871	26,264	0.99	64,223	0.00	164
-1	6.5	76,666	31,039	10.92	837,085	0.03	2,056
1	7	82,564	33,427	10.92	901,476	0.03	2,214
2	7	82,564	33,427	10.92	901,476	0.03	2,214
3	7	82,564	33,427	10.92	901,476	0.03	2,214
4	7	82,564	33,427	10.92	901,476	0.03	2,214
5	7	82,564	33,427	10.92	901,476	0.03	2,214
6	7	82,564	33,427	10.92	901,476	0.03	2,214
7	7	82,564	33,427	10.92	901,476	0.03	2,214
8	7	82,564	33,427	10.92	901,476	0.03	2,214
9	7	82,564	33,427	10.92	901,476	0.03	2,214
10	7	82,564	33,427	10.92	901,476	0.03	2,214
11	7	82,564	33,427	10.92	901,476	0.03	2,214
12	7	82,564	33,427	10.92	901,476	0.03	2,214
13	7	82,564	33,427	10.92	901,476	0.03	2,214
14	7	82,564	33,427	10.92	901,476	0.03	2,214
15	7	82,564	33,427	10.92	901,476	0.03	2,214
16	7	82,564	33,427	10.92	901,476	0.03	2,214
17	7	82,564	33,427	10.92	901,476	0.03	2,214
18	7	82,564	33,427	10.92	901,476	0.03	2,214
19	7	82,564	33,427	10.92	901,476	0.03	2,214
20	7	82,564	33,427	10.92	901,476	0.03	2,214
21	7	82,564	33,427	10.92	901,476	0.03	2,214
22	7	82,564	33,427	10.92	901,476	0.03	2,214
23	6.75	79,615	32,233	10.92	869,281	0.03	2,135
24	5.75	67,820	27,458	10.28	697,287	0.03	1,708
25	4.75	56,025	22,682	9.95	557,211	0.02	1,365
26	3.75	44,230	17,907	9.95	439,904	0.02	1,078
27	2.75	32,436	13,132	9.93	322,040	0.02	789
28	1.75	20,641	8,357	9.93	204,935	0.02	502
29	0.75	8,846	3,581	9.93	87,829	0.02	215
30	0	-	-	-	-	0.80	-
Averages		65,270	26,425	8.85	650,144	0.04	1,597

4.2 Base Case Biomass Transportation Assumptions

Most industries use multiple forms of transportation. The two forms of transportation assumed for this study are trucks and trains. The base case assumes that the majority of the transportation needs will be met using trucks; 70% of the wood is delivered by trucks and 30% is delivered by trains. In general, the mix of transportation used to haul the biomass from the fields to the power plant will be site-specific. For the base case, the biomass yield is 13.5 dry Mg/ha/year (6 dry tons/acre/year) and the biomass haul losses are assumed to be 4.62% (Perlack *et al*, 1992). Using these numbers the amount of as-received wood containing 50% moisture that is transported to the biomass power plant is 814,282,029 kg/year for an operating capacity of 80%. The capacity of each truck is 23 Mg (25 tons); rail transport is assumed to be by conventional freight trains made up of 85 cars with 17 of the cars carrying 77 Mg (85 tons) of wood each. This results in 25,133 truck deliveries and 186 train deliveries to the plant per year. Although the number of truck deliveries (average of 69 per day) is not outside of the range at current operating facilities, if it is deemed to be more than what a community will accept, the number of train deliveries could be increased.

The inventory assessment for the transportation subsystem includes the energy required and emissions generated for the transportation of chemicals, biomass, and other items by truck and train between the boundaries of the biomass production and power generation subsystems. Any transportation requirements within the boundaries of the biomass production and power generation subsystems are included in the inventory assessment for that subsystem. For the base case, the average distance traveled was calculated to be 27.6 km. This calculation assumes that 10% of the land around the power generation facility is available for crop production and that the land has a tortuosity factor of 1.3. The trucks and trains use diesel and light fuel oil as the fuel source, respectively. The energy and emissions related to extracting crude oil, distilling it, producing a usable transportation fuel, and distributing it to refueling stations plus the emissions produced during combustion of the fuel were included in the total inventory. These data were taken from the DEAM database, of which some details are shown in Appendix B.

There are several ways to handle the emissions associated with vehicle production and decommissioning. One option would be to evenly distribute the emissions associated with these two processes over the lifetime of the plant. Another option would be to account for the emissions in the year that the vehicles are actually produced and disassembled. The latter option is the way in which the emissions were handled in this life cycle assessment.

Table 16 shows the primary materials used in the production of trucks and trains (Dyncorp, 1995). Steel is the main component for both of these modes of transportation.

Table 16: Truck and Train Material Requirements

Material	Amount required (kg/truck)	(kg/rail car)
steel	13,789	6,713
iron	272	
aluminum		45

The lifetime of a train is considered to be 6.08 million km (3.78 million miles) (DynCorp, 1995), which is equivalent to 30 years. Therefore, the emissions associated with train construction are taken into account in year one and the rail cars are decommissioned in year 30, the last year of operation. The lifetime of a truck is 540,715 km (336,000 miles) (DynCorp, 1995; Delucchi, 1993), which is about 7.5 years for this analysis. The truck bodies are shredded or crushed and used as scrap metal in secondary metal production operations.

According to the Motor Vehicle Manufacturers Association (1995), 75% of the truck and train material content is recycled after disassembly. This fraction of the stressors that are normally produced in manufacturing trains and trucks from virgin materials is taken as a credit in the LCA inventory. These are the emissions and energy consumption avoided because of the recycling process. In balance, the stressors produced in the recycling operations themselves are added to the total life cycle inventory. Landfill emissions, for example, come from diesel oil used in shredding and compacting material that would normally be disposed of were it not for recycling. Another example is the electricity consumed to separate metals and other materials. The metals recovered from the trucks and rail cars displace metals production from both scrap and ore with 50% of the metals split to each. Displacing metals production from ore results in larger credits than those taken for scrap because of stressors associated with ore extraction and transportation that are not associated with scrap recycle.

4.3 Base Case Power Plant Construction & Decommissioning Assumptions

For this analysis, the plant is being constructed over a two year period with startup at 40% (50% of 80%) operation in year one. During the years following construction the plant will operate at an 80% capacity factor. The life of the plant is assumed to be 30 years and during the last year the plant will be in operation 60% (75% of 80%) of the time because of decommissioning in the last quarter of that year.

During construction, emissions of particulate matter will be high due to the activities associated with land preparation, drilling and blasting, ground excavation, earth moving, and construction itself. A large portion of the particulate emissions also result from equipment traffic over temporary roads. The total amount of particulates during construction is equivalent to 2.6 Mg per hectare of site area per month of activity. Wet suppression of the land is used to control particulate emissions from the construction site and road paving will begin in the first year of construction. All of the asphalt surfaces are composed of compacted aggregate and an asphalt binder (U.S. EPA, 1995). The primary pollutants of concern from the asphalt paving operations are VOCs. There are two types of asphalts: cutback and emulsified. Cutback asphalts, which have been the primary asphalt used in the past, contain petroleum distillate solvents which are released into the atmosphere during the curing process. Emulsified asphalts rely on water evaporation for curing thus minimizing any hydrocarbon emissions. For this analysis, it is assumed that an emulsified asphalt is used since it is appropriate for almost any type of asphalt application. Particulate and asphalt emissions associated with construction were built into TEAM using data from several literature sources (U.S. EPA, 1995 and Ullman's Encyclopedia of Industrial Chemistry).

Table 17 shows the primary materials used for constructing the power plant (Dyncorp, 1995). Concrete and steel are consumed in the largest quantities.

Table 17: Plant Material Requirements (Base Case)

Material	Amount required (kg/GWh electricity produced)
concrete	22,299
steel	8,341
aluminum	65
iron	97

Because it is the most common type of cement used for structural applications, gray portland cement was assumed for the construction of the plant. The cement manufacturing is divided into the following processes: raw materials acquisition and handling, kiln feed preparation, pyroprocessing, and finished cement grinding (U.S. EPA, 1995). More than 30 raw materials are used in manufacturing cement, most obtained from open-pit quarries or mines. However, some are acquired through underground mines or dredging operations. The raw materials are delivered to the plant and the cement is batched on site. Particulate matter from cement dust and sand aggregate is the primary pollutant generated in this step. These emissions, along with the air emissions and energy requirement from the other processing steps, were input into TEAM from the information contained in the U.S. EPA (1995) reference.

4.4 Base Case Power Generation Assumptions

The inventory assessment for the power generation subsystem begins at the plant gate of the power plant and ends with the production of electricity. The boundaries, process configuration, and emissions for the power generation subsystem can be seen in Figure 6. The primary air emissions were determined using the material and energy balances from the ASPEN Plus™ simulation. Additional emissions such as particulates and VOCs as well as upstream energy requirements for items such as sand were calculated from estimates in various literature sources and documented studies (Weyerhaeuser *et al*, 1995 and Boustead and Hancock, 1979). Table 18 gives a summary of the power plant operating emissions which were used in this study.

Figure 6: General Sources of Power Plant Emissions

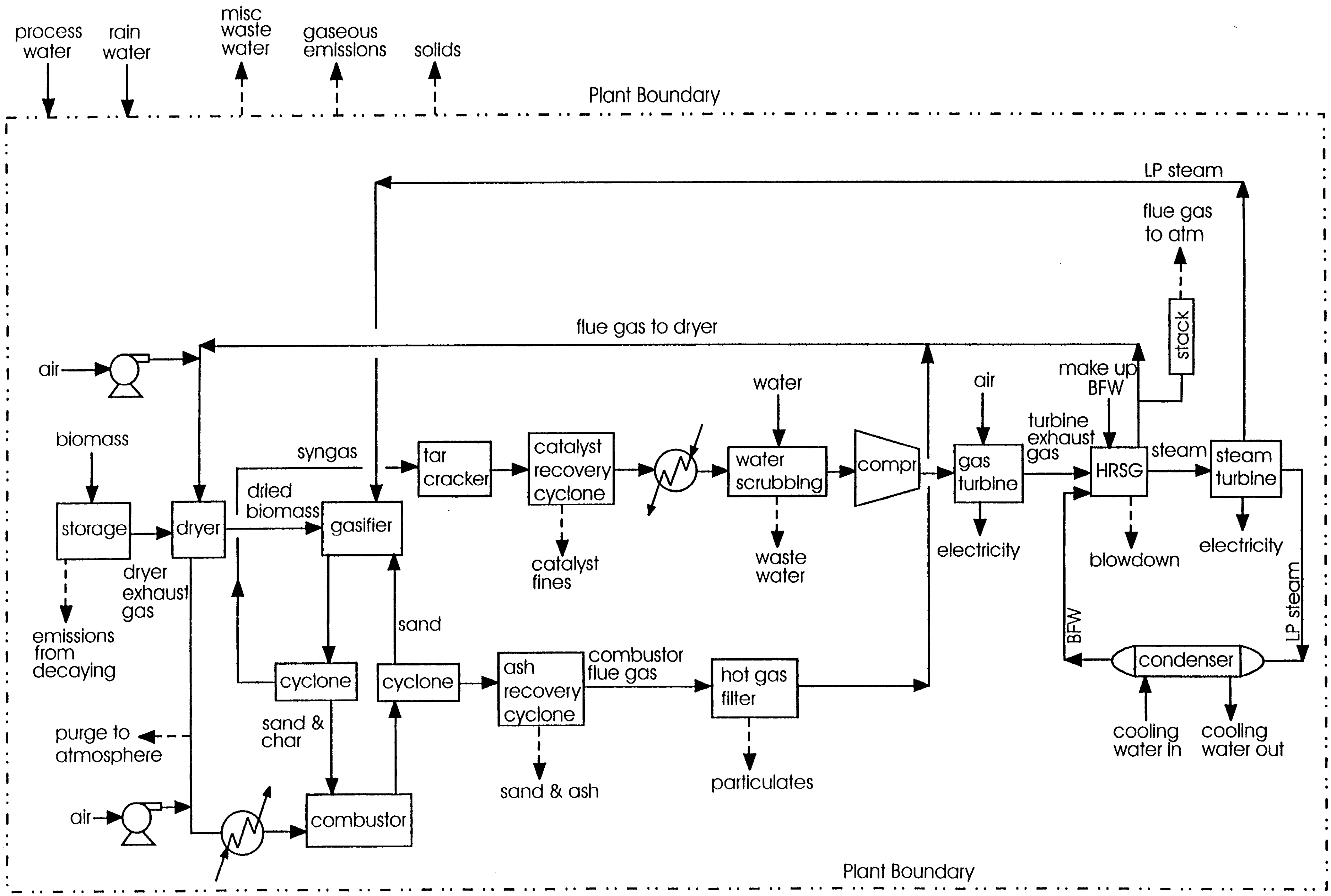


Table 18: Power Plant Operating Emissions (Base Case)

Compound	Emission Amount (kg/GWh)	Primary Emission Source	Reference
NOx	479	gas turbine	ASPEN© simulation
SOx	254	gas turbine	ASPEN© simulation
HC (except CH_4)	0.53	char combustor	Weyerhaeuser 1995
CO	0.86	char combustor	Weyerhaeuser 1995
CH_4	0.27	char combustor	Weyerhaeuser 1995
CO_2	916,224	char combustor and gas turbine	ASPEN© simulation
particulates	3.7	feed prep and dryer	Weyerhaeuser 1995
VOCs	515	dryer	Weyerhaeuser 1995

4.4.1 Biomass Storage & Drying

Biomass is delivered to the plant and unloaded to a paved storage yard. The amount of wood delivered to the plant was set based on the gas turbine design requirements and biomass haul losses. Because biomass is not harvested throughout the year but is required at the plant on a continuous basis, storage is required. It was assumed that the majority of the storage occurs at the plantation, while a three-week supply of chips is maintained at the plant. In order to mitigate degradation and any associated emissions, biomass stored for periods longer than three months is assumed to be kept in whole-tree form (Kropelin, 1997).

Before being gasified, the biomass is dried in a rotary kiln dryer using a mixture of air, the combustor flue gas, and a majority of the flue gas from the HRSG. To reduce wood dust and VOC emissions, a slipstream of the dryer exhaust gas is used as part of the combustion air source for the char combustor (see Figure 5 and 6). This configuration is a change from the original design as reported in Craig and Mann (1996). The ASPEN Plus™ model demonstrated that it was not feasible to recirculate the total dryer exhaust gas stream to the char combustor because the oxygen content of this stream is only 10 mol%. Fresh air was added to bring the oxygen content up to 17 mol% in accordance with burner manufacture requirements, resulting in a 9% (weight basis) recycle of the dryer exhaust gas.

It has been hypothesized that more hydrocarbons will be emitted with increased removal of wood moisture content, and that as the wood dries more wood dust will be generated (Adams *et al*, 1971; Blosser 1986). The wood is dried to 11 wt% moisture, which should produce lower levels of hydrocarbons and particulate emissions than wood drying for lumber, particleboard, flakeboard, oriented strandboard, hardboard, and veneer. These industries are required to dry the wood to very low moisture concentrations of less than 5 wt% (Prodehl and Mick, 1973; Adams *et al*, 1971; Blosser 1986). Many of the concerns associated with wood drying can also be traced back to contamination of the wood source. This contamination typically comes from pieces of sawmill machinery, floor sweepings, chemicals, and wood finishes (Schultz and Kitto, 1992). Using wood chips from freshly cut trees instead of waste wood will minimize contamination and corresponding harmful emissions.

4.4.2 Gasifier/Combustor

Most of the emissions from the gasification step (including char combustion) were determined by the elemental composition of the wood. All of the nonhydrocarbon emissions, except NOx, will be limited to the amount of sulfur, ash, alkalis, and heavy metals in the feedstock. The elemental sulfur, which is typically less than 0.1 wt% of the wood on a dry basis, has the potential to form hydrogen sulfide (H_2S) and SOx. Two nitrogen sources, that in the feedstock (on the order of 0.5 wt%) and that in the combustion air, have the potential to form NOx in the gasification/combustion step. The initial formation of NOx from the fuel-bound nitrogen will be a function of the amount of excess air, the heat release rate, and the fuel moisture content (Schultz and Kitto, 1992). Thermal NOx is typically formed at high temperatures, in the neighborhood of 1,204°C (2,200°F). Because the char combustor operates at 982°C (1,800°F), the majority of NOx from the combustor will come from the feedstock. Most thermal NOx from this system will be formed primarily in the gas turbine combustor (discussed in section 4.4.3).

The heat necessary for the endothermic gasification reactions is supplied by sand circulating between the fluidized bed char combustor and the gasification vessel. Although sand is sometimes used in its raw state, most sand is processed prior to use. For this study, the basic operations involved are assumed to be mining, screening, crushing, and washing. Sand is typically mined under wet conditions by open pit excavation or by dredging, and emissions are primarily particulate matter. Many industrial sand facilities use control devices such as cyclones, wet scrubbers, venturi scrubbers, and fabric filters in an effort to minimize particulate emissions.

The products of the gasification step are synthesis gas, char, and ash. The product gas exits the gasifier overhead while greater than 99.5% of the char and ash are captured with the sand and circulated back to the combustor. The combustor flue gas is sent through a recovery cyclone to remove any residual sand and ash that are carried overhead prior to being sent to the atmosphere. Even though the solids captured in the cyclone are mainly sand, the ash content includes trace amounts of alkalis and heavy metals. The amount of metals in the biomass will depend on the growth environment (Tillman and Prinzing, 1994; Golam *et al*, 1993). Generally, high heavy metal concentrations in biomass ash have been traced to combustion sources where non-wood wastes are mixed with "clean" wood and then burned (Tillman and Prinzing, 1994; McGinnis *et al*, 1995). Heavy metal content in the ash is assumed to be negligible because only clean wood from the plantation will be used and because the amounts that might be present are so small they will not affect the end use of the sand and ash mixture.

There has been much speculation regarding uses for biomass ash. It has the potential to be used as a clarifying agent in water treatment, as a wastewater adsorbent, as a liquid waste adsorbent, as a hazardous waste solidification agent, as a lightweight fill for roadways, parking areas, and structures, as an asphalt mineral filler, or as a mine spoil amendment (Fehrs and Donovan, 1993). The most sought after use is to landspread the ash on farms in the hopes of utilizing its nutrient mineral content. Because the stream from this system is nearly 100% sand, however, it is likely that these means of disposal would not be feasible. For this analysis, the sand and ash mixture from the cyclones is assumed to be used in asphalt production for roads, as is the plan for the demonstration facility at the McNeil power plant in Burlington, Vermont. The appropriate credits and stressors for using this material instead of virgin material in asphalt production are taken in this LCA.

4.4.3 Gas Turbine and HRSG

The gas turbine emissions consist of NOx, SOx, CO, CO_2, unburned hydrocarbons, VOCs, and particulates. The sulfur and nitrogen compounds contained in the biomass-derived synthesis gas are converted to SOx and NOx in the gas turbine combustor. As discussed earlier in the gasifier/combustor section, fuel-bound NOx cannot be completely eliminated with existing emissions control technology, and because the gas turbine firing temperature is 1,288°C (2,350°F), thermal NOx will be generated. No special emissions-control technologies were assumed in the design of this plant. Therefore, the NOx reported represents a conservative case. For the base case, it was assumed that all of the sulfur and all of the nitrogen contained in the biomass was converted to SOx and NOx, respectively. A sensitivity analysis was performed to account for the possible formation of thermal NOx. Additionally, there will be unburned hydrocarbons and VOCs at the parts-per-million level.

The stack is located on the exhaust from the HRSG. A large portion of the flue gas exiting the HRSG is used to dry the biomass. Therefore, the gas released to the atmosphere is a combination of dryer and gas turbine combustion emissions. Wastewater is also produced from the boiler blowdown, and sent to the wastewater treatment step to be processed into discharge-quality water.

4.4.4 Water Requirements & Treatment

The water requirements for the plant include recirculated quench water, boiler blowdown, cooling water, and miscellaneous water such as utility, potable, and fire water. Once used, water is collected and treated in a wastewater treatment step to produce an effluent that can be reused within the plant or discharged without causing serious environmental impacts.

Prior to compression, the synthesis gas is cooled through heat exchange and water scrubbing. The scrubbing condenses any residual tars that remain after the synthesis gas has passed through the tar cracker. The quantity and composition of the tars depends on the type of gasifier and the operating conditions. The tars that are expected from the BCL/FERCO gasifier consist of more thermally labile "secondary tar" components such as phenol, styrene, and toluene (Gebhard *et al*, 1994). The wastewater may also contain ash, char, or sand that were not removed in the gasifier cyclone, tars not converted in the tar cracker, and a small quantity of tar cracker catalyst fines. Any carryover of particulates is expected to be in the parts-per-million range. Water from the scrubbing step is sent to a separation tank, where insoluble tars are skimmed off of the water and fed back to the char combustor. A portion of the remaining water is used to rehumidify the synthesis gas prior to combustion in the gas turbine. This reduces the amount of water that must be treated and increases the power output from the plant. The remaining water is then treated in the wastewater treatment step.

Physical, chemical, and biological processes are the possible options for treating the wastewater streams. Further defined, physical operations are used to remove floatable and settleable solids, biological and chemical processes are used to remove most of the organic matter in the wastewater, and tertiary systems are used to remove any process constituents that are not taken out in secondary treatment. A combination of each of these was assumed to be used in the power plant. The concentration of organic chemicals from the power plant is anticipated to be low enough that secondary biological treatment will not be necessary, only primary treatment for solids removal. The wastewater is collected through a series of drains, trenches, and sumps that are connected to a main line. Collection systems such as this are generally open to the atmosphere, allowing some VOCs to be emitted. Many factors affect the rate of volatilization of organic compounds from the wastewater, including water surface area, temperature, turbulence, and concentration of organics, to name a few. Determining the rate of volatilization of each organic compound was not done for this study; thus, VOC emissions from wastewater were assumed to be zero.

5.0 Base Case Results by Impact Category

Although the material and energy balances for each of the three subsystems (biomass production, transportation, and electricity generation) were examined for each year of production, the resulting impacts were averaged over the life of the system to examine the relative percent of emissions from each. The average amount of emissions produced, resources consumed, and energy used by each of the subsystems per unit of energy delivered by the power plant can be seen in Tables 19 through 23. It should be noted that only the stressors that were of significant quantity are reported in these tables. Furthermore, these numbers appear to be definitive, while if data for a particular stressor were not available for all blocks, total stressors are being reported as lower than they actually are. The absence of data is specifically spelled out in this report.

In years negative seven through negative three all of the resources, emissions, and energy are associated with feedstock production. As expected, there is a yearly increase as the number of fields in production increases by one each year. The stressors then tend to be level in the positive years even with the construction and decommissioning activities associated with the farm equipment and truck transportation. Finally, a gradual decrease is seen, starting in year 23 when biomass production tapers off, leading up to a rapid decrease in impacts during final decommissioning. A majority of the resources, emissions, and energy are higher in years negative one and negative two due to the activities associated with plant construction.